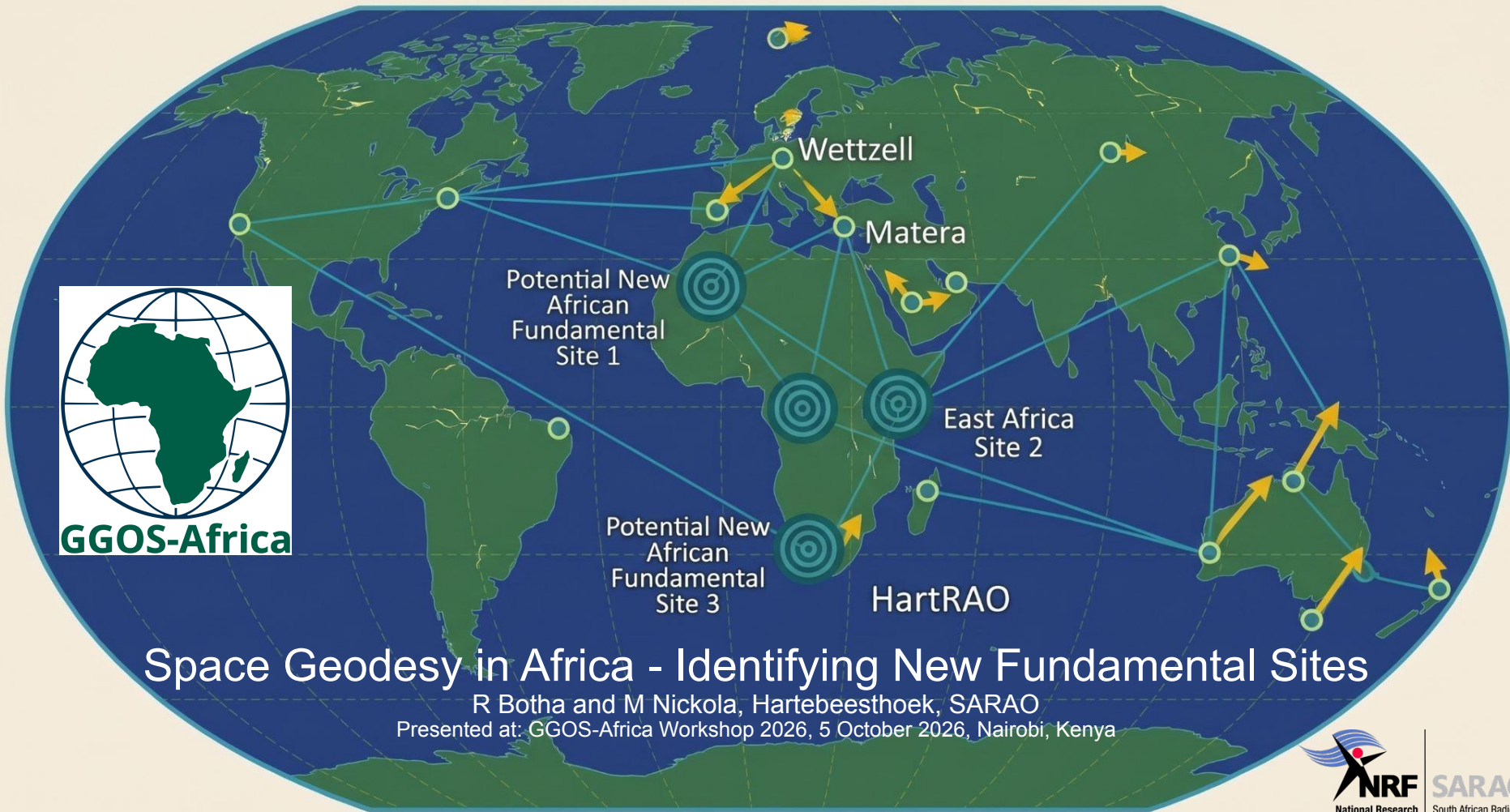




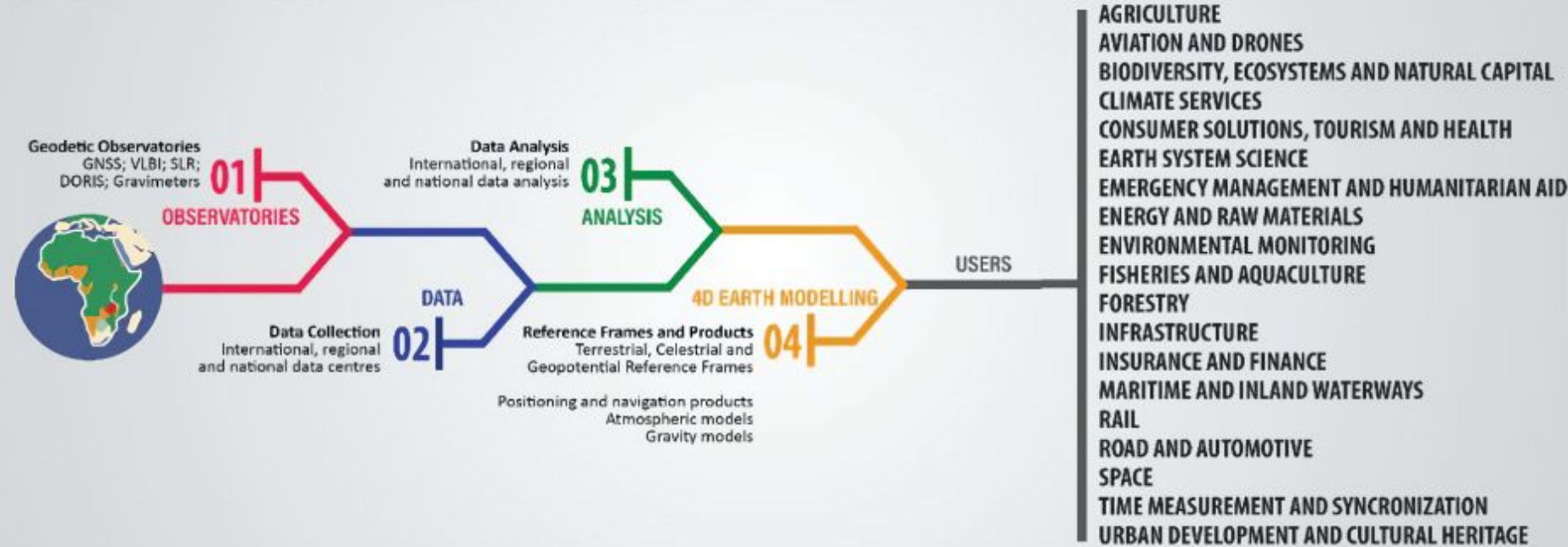
Space Geodesy in Africa - Identifying New Fundamental Sites

R Botha and M Nickola, Hartebeesthoek, SARAO

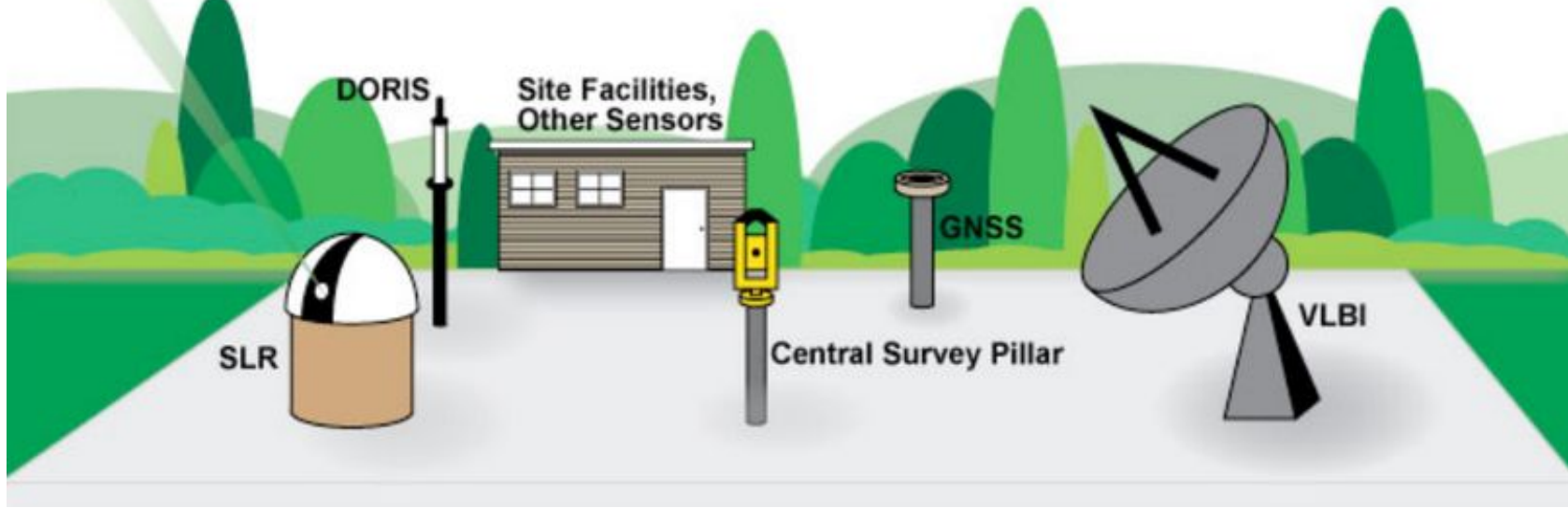
Presented at: GGOS-Africa Workshop 2026, 5 October 2026, Nairobi, Kenya

0. TIME and POSITION products are required by nearly all aspects of modern society...

GLOBAL GEODESY SUPPLY CHAIN



0. Space Geodetic Fundamental Sites



- Geodetic VLBI (international network): determines inter-telescope baselines (therefore accurate positions)
- Use this position to determine position of each of the other instruments on-site by terrestrial techniques (Survey)

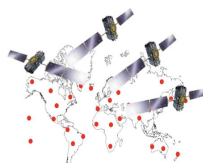
The other techniques are then used to determine various position and time values:

- Satellite Laser Ranging: actual satellite orbit segments
- The GNSS reference stations - since the actual position has been determined via VLBI and surveying techniques, the offset with the GNSS-derived position is then used to quantify the other influencing factors like atmospheric pressure, ionosphere etc.
- DORIS transmit reference signals to space, for other satellites to determine their positions from it

0. Space Geodesy techniques and parameters linked to EOPs



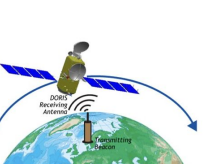
VLBI
Very Long Baseline Interferometry
 Earth rotation, station coordinates, quasar positions



GNSS
Global Navigation Satellite Systems
 (GPS, GLONASS, Galileo, Beidou)
 Station coordinates, Earth rotation, Geodynamics



SLR
Satellite Laser Ranging
 Satellite orbits, station coordinates, Earth rotation, centre of mass of the Earth

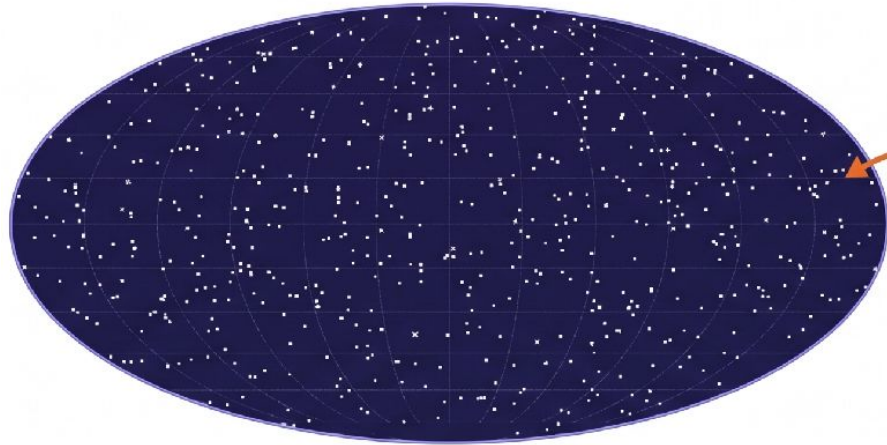


DORIS
Doppler Orbitography and Radiopositioning Integrated by Satellite
 Satellite orbits, Station coordinates, Earth rotation, gravity field

Parameter type	VLBI	GPS/ GLON.	DORIS/ PRARE	SLR	LLR	Alti- metry
Quasar Coord. (ICRF)	X					
Nutation	X	(X)			X	
Pole Coord. X, Y	X	X	X	X	X	
UT1	X					
Length of day (LOD)		X	X	X	X	
Sub-daily ERPs	X	X				
ERP Amplitudes of ocean tides	X	X		X		X
Station Coord.+ Velocities (ITRF)	X	X	X	X	X	(X)
Geocenter		X	X	X		X
Gravity field		X	X	X	(X)	X
Satellite orbits		X	X	X	X	X
LEO orbit determination		X	X	X		X
Ionosphere	X	X	X			X
Troposphere	X	X	X			X
Time/Frequency transfer	(X)	X	X			

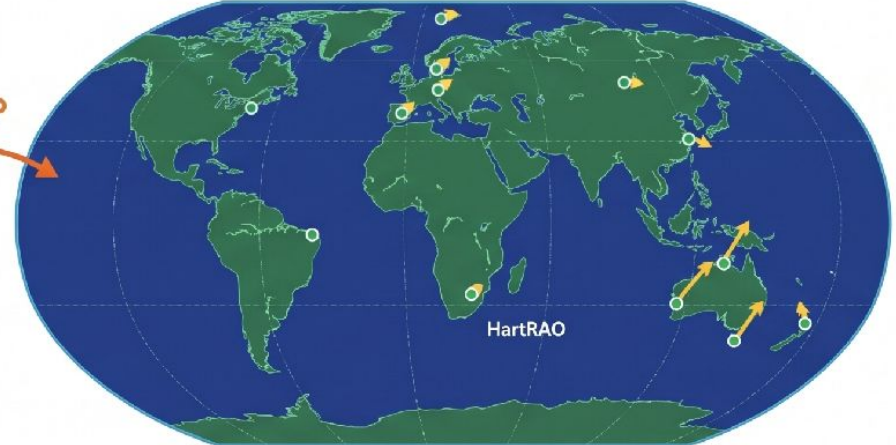
0. EOPs linking the ICRF and ITRF

Map of the sky
ICRF



Positions of distant quasars,
fixed in space

Map of the Earth
ITRF



Where our stations are, and how they move
as the continents drift

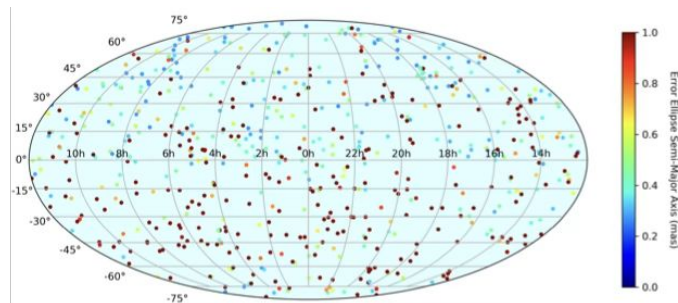
EOP

The Earth Orientation Parameters tell us how one map is turned relative to the other at any moment.

0. The International Celestial Reference Frame

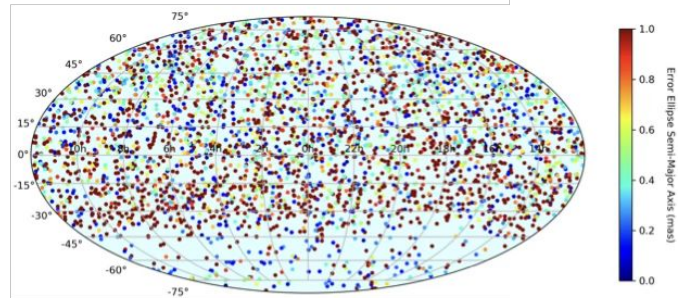
ICRF1-SX (2.3/8.4 GHz, 3.6cm)

(Ma et al., 1998)



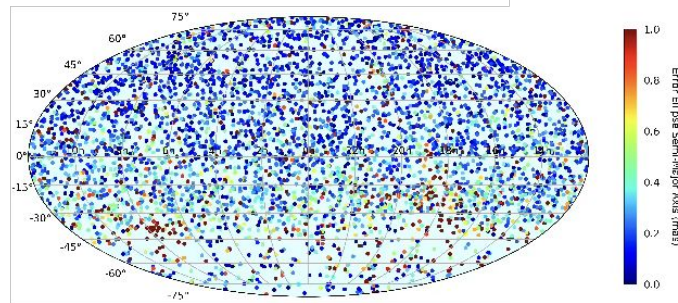
ICRF2-SX (2.3/8.4 GHz, 3.6cm)

(Fey et al., 2015)



ICRF3-SX (2.3/8.4 GHz, 3.6cm)

(Charlot et al. 2020)



ICRF1 **1998 Jan 01**
Nsources 608
Ndefining 212
Noise floor: 250 μ as in RA/Dec

ICRF2 **2010 Jan 01**
Nsources 3414
Ndefining 295
Noise floor: 40 μ as in RA/Dec

ICRF3 **2019 Jan 01**
Nsources 4536
Ndefining 303
Noise floor: 30 μ as in RA/Dec

(Overview paper, de Witt et al., 2022)

Work Package 3 - Simulation and strategic planning for infrastructure development

Utilise simulations and geospatial analysis to identify optimal locations for new geodetic infrastructure and develop a strategic plan for infrastructure enhancement in conjunction with work package five.

Proposed Implementation:

1. Simulations development
2. Geospatial analysis
3. Strategic plan development
4. Stakeholder consultation

Deliverables:

1. Simulations and models for infrastructure planning.
2. A strategic infrastructure development plan is to be presented at the planned workshops to relevant stakeholders.
3. Stakeholder engagement reports

Work Package 3 - Simulation and strategic planning for infrastructure development

Utilise simulations and geospatial analysis to identify optimal locations for new geodetic infrastructure and develop a strategic plan for infrastructure enhancement in conjunction with work package five.

Actual Implementation:

Proposed Implementation:

1. Simulations development
2. Geospatial analysis
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1. Simulations Development
2. Geospatial analysis
3. Simulations
4. Stakeholder consultation
5. Strategic plan development

(Note: like the 0th law of Thermodynamics, I had to number my initial section as 0...)

Deliverables:

1. Simulations and models for infrastructure planning.
2. A strategic infrastructure development plan is to be presented at the planned workshops to relevant stakeholders.
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SECTION 1:

Initial analysis → ***GGOS fundamental sites are the most important factor***
We first need to ‘survey’ the Earth in the Celestial Frame

- Global supply chain starts with Observatories (Space Geodetic), observing Quasars
- Approach now that we know this: Where to add another FUNDAMENTAL SITE in Africa?

Order of importance for GGOS fundamental sites:

- 1. VLBI - quasar measurements (RFI and bedrock requirements)**
- 2. SLR - need clear skies**
3. GNSS + DORIS: can work most places

Considerations for Fundamental Sites (from *Site Requirements for GGOS core Sites*, Revision 1a of July 18, 2012):

- Global
- Land
- Sky

1. GGOS - fundamental site requirements as considered towards simulations

1. Global Considerations		
	Geometric Distribution: homogeneous	Considered
	Technique-dependent distribution for VLBI and SLR	Considered
	Tectonic Distribution: 3 per plate	Partially
2. Land Considerations		
	Geology, horison, not near large bodies of water	Considered
	Infrastructure: Power, roads and fibre internet	Considered
3. Sky considerations:		
	Weather and sky conditions (Cloud fraction, PWV, Atmospheric Optical Depth)	Qualitatively
	Interference: optical (SLR), RFI (VLBI), air traffic (both)	Qualitatively

SECTION 2:

GGOS - Our approach for simulations

- Choose one potential ‘very good’ new fundamental site per country, as per considered parameters
- 3 Base Scenarios:
 1. **CURRENT**: Current VGOS network (In Africa, only HartRAO)
 2. **NEAR FUTURE**: As in **CURRENT** + add all international sites that will be online soon (currently under construction / near completion) [Africa → added Nigeria’s TORO site]
 3. **FAR FUTURE**: **NEAR FUTURE** + add internationally planned / funded sites
- Use **VieSched++** [1] to simulate as follows:
 - a. Set up a generic R1 + R4 experiments (EOPs) for **CURRENT** base scenario
 - b. Add a single African TEST VGOS dish
 - c. Ran a simulation (1000 runs) to generate EOP parameters → Record + add dot on the map
 - d. Repeat this for another TEST site in Africa, until list of test sites have all been simulated for individually

[1] [Matthias Schartner and Johannes Böhm, 2019 PASP, 131 084501](#), DOI 10.1088/1538-3873/ab1820

2. Simulation outputs

- Mean formal errors
 - Repeatability
- of the following parameters:
- EOPs
 - station coordinates

Parameter (EOP)	Improvement due to:
UT1 - UTC	Decrease
Pole position X,Y (arcsec x 10 ⁻⁶)	Decrease
Nutation X,Y (arcsec x 10 ⁻⁶)	Decrease
3D Station Coordinate ¹	Seemingly Ambiguous *
Number of possible observations ¹	Seemingly Ambiguous*

*Remember Global Consideration #1 of equi-distribution:

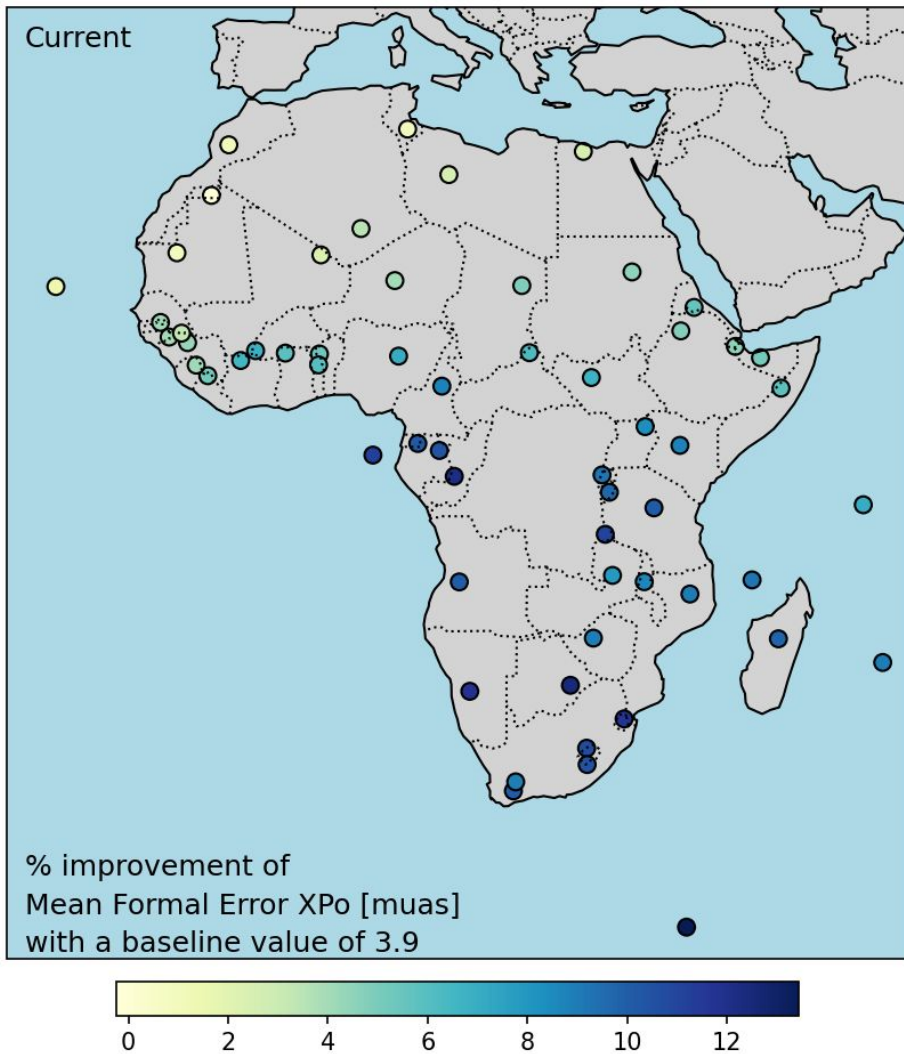
If stations were very close together, they will:

- give each other better relative 3D positions and
- be able to observe EVERY source together,
- there are less sources in the ICRF-South → less observations

So we look for sites that minimise these effects, in order to:

- Improve geographic distribution
- Help densifying the ICRFs Southern-sky source map

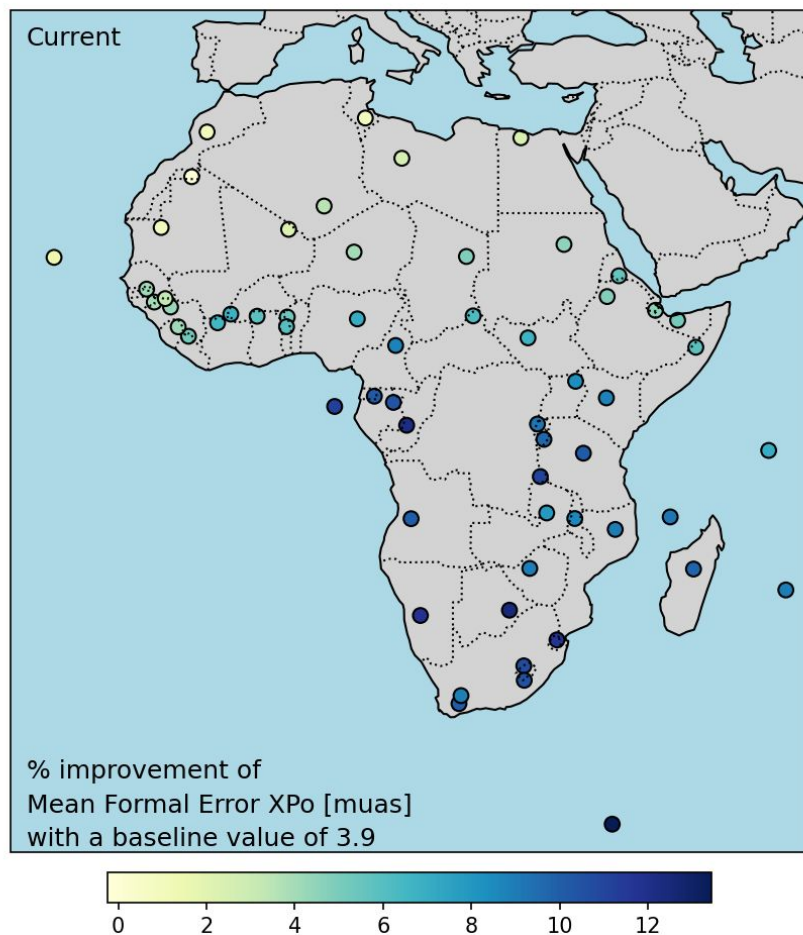
¹Not an EOP, but used in conjunction with it in the simulations



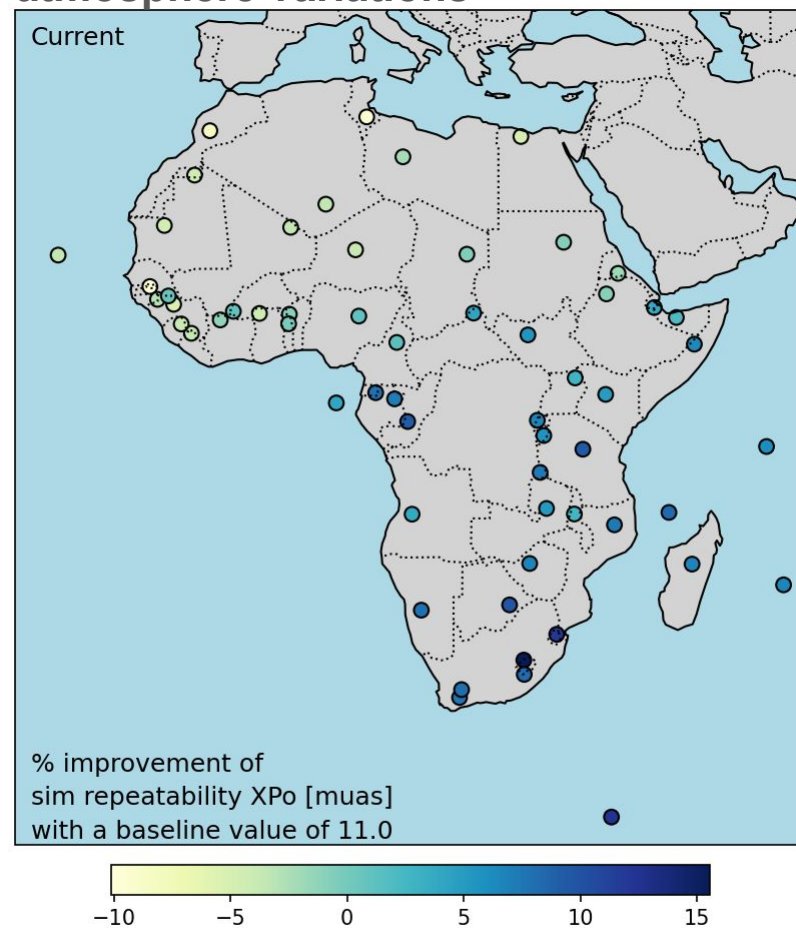
2. Explanation of output

1. The current VGOS network is NOT represented here- this gives the BASELINE value ($3.9 \mu''$)
2. Each dot needs to be interpreted separately
3. X-pole: decrease in value $\rightarrow$ Improvement
4. Values reworked to % relative to Baseline value

2. MFE: Mathematical approach

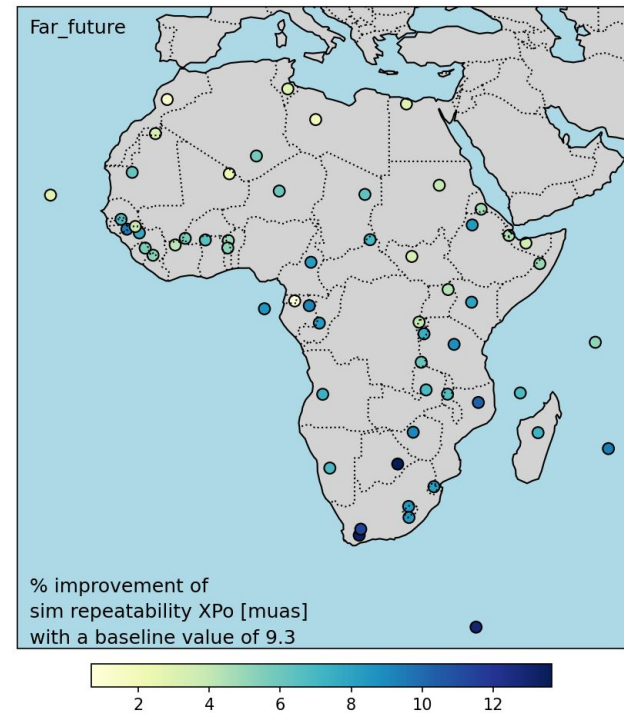
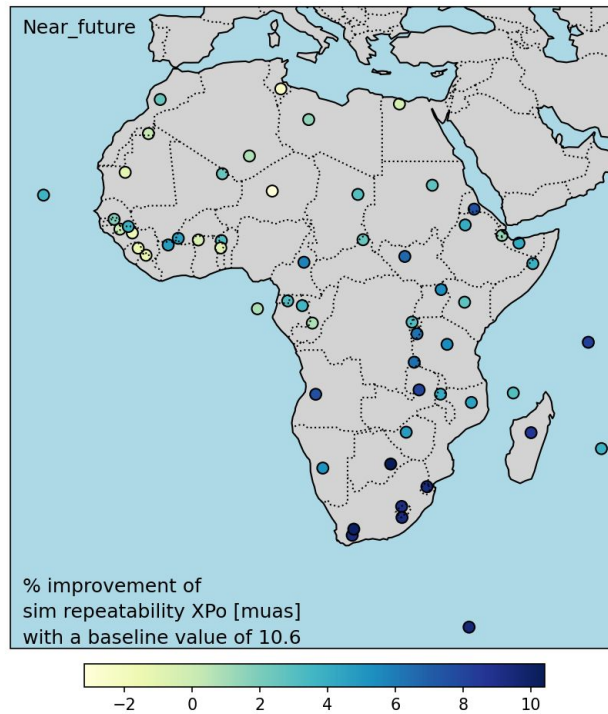
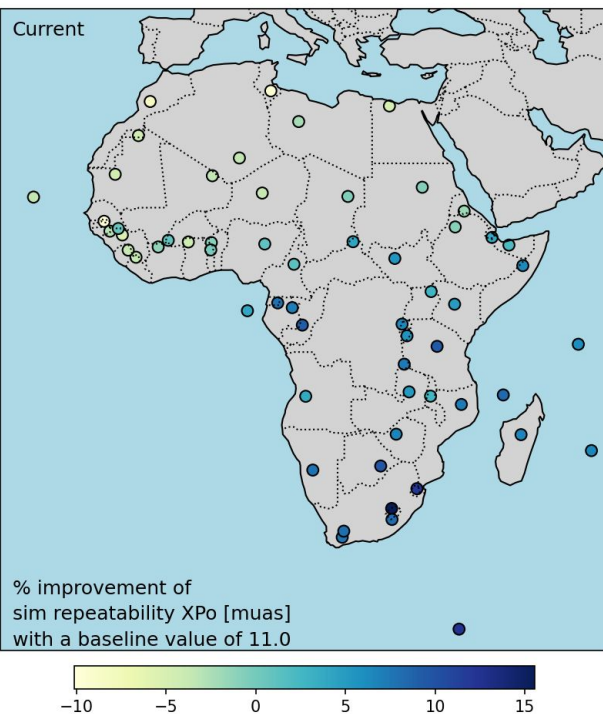


Repeatability: simulate for clocks and dry atmosphere variations

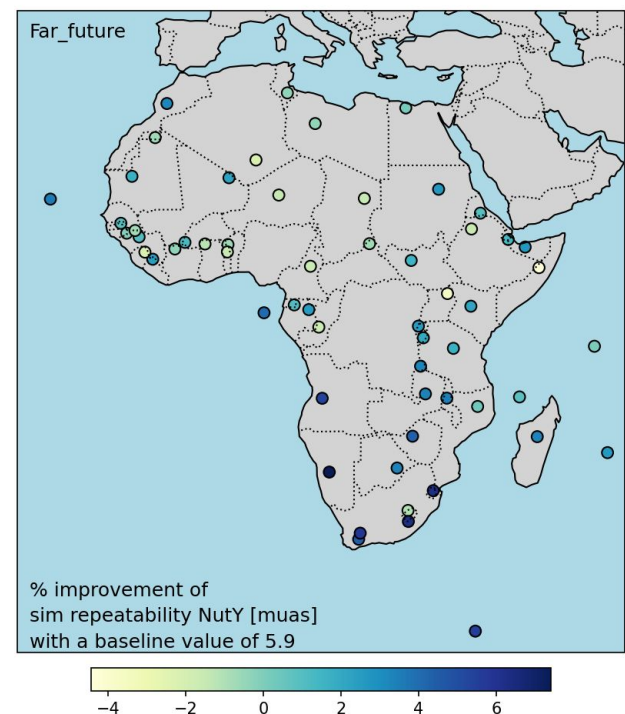
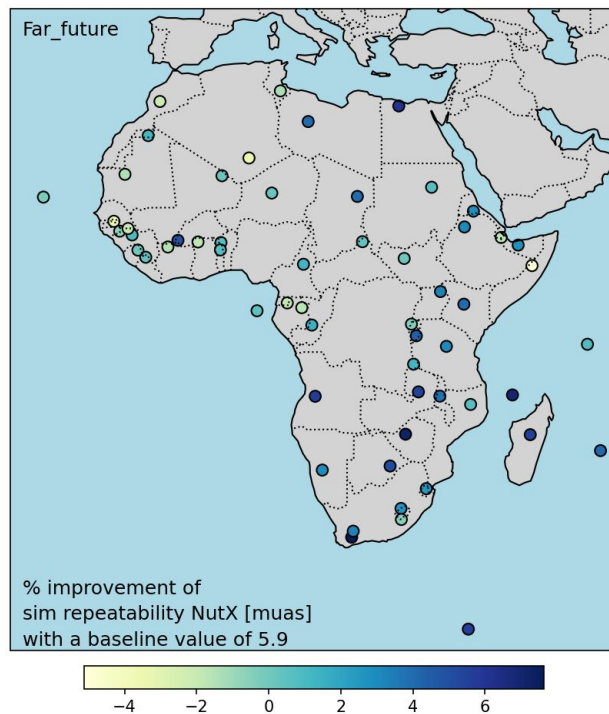
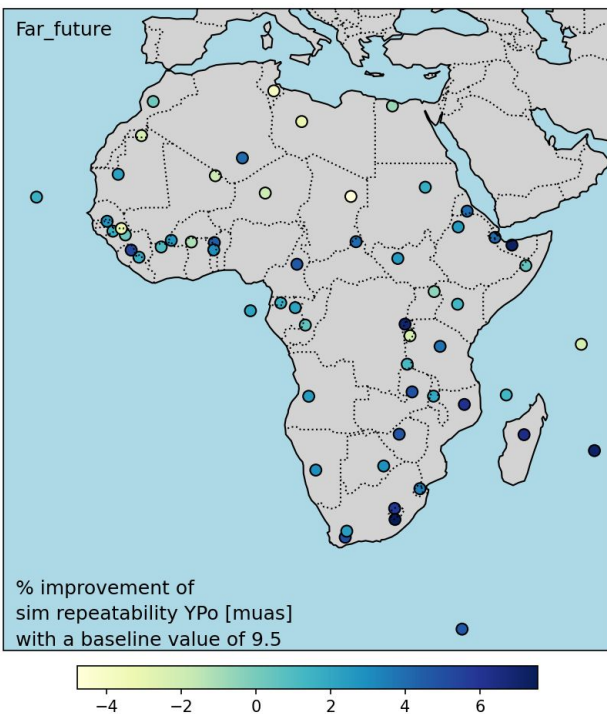


2. Time-evolution of Repeatability of the X-pole parameter simulation

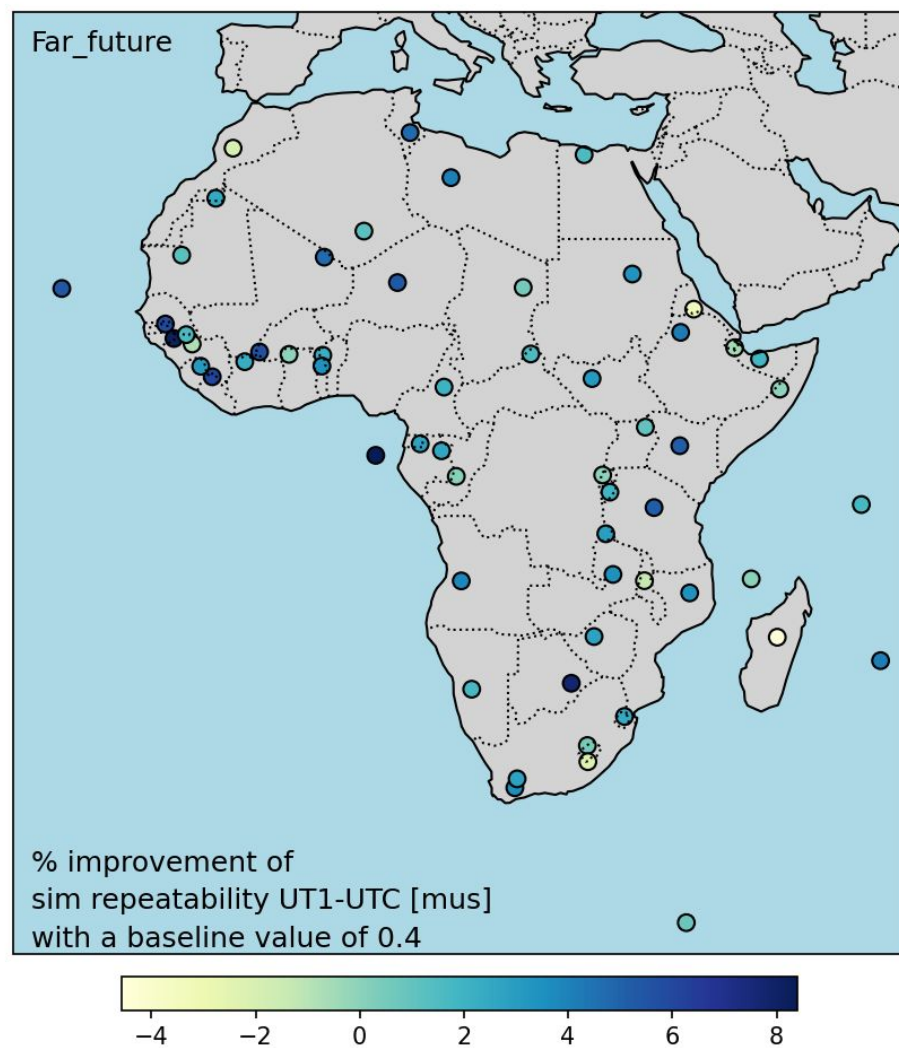
Far Future scenario
is the one to consider



2. Other relevant EOPs to consider for the far future



2. Other relevant EOPs to consider: UT1 - UTC



2. Adding one new VGOS (per African country)

Summary

- Taking GGOS fundamental site requirements into account, filtering as follows:
 - first VLBI/VGOS - stable bedrock, low RFI, low elevation horizon mask, infrastructure
 - then SLR - high clarity, low PWV, air traffic corridors
 - followed by GNSS and DORIS - multipath avoidance and clear hemispheric viewing arcs, 150–300 meter perimeter separation distance
- Strategy: start with 'very good' locations for VGOS and SLR
- Simulated for one new potential (very good) site per country

Conclusions

- Adding Fundamental site anywhere on continent yields improvement
- 5 Stations with a good spread is probably the least we should aim for
- Critical to monitor the divide between the Nubian and Somalian plates
- The network reaches structural saturation - performance difference between #1 and #10 spots shrinks dramatically

SECTION 3:

Approach simulations from an Africa-only perspective

What if Africa ever needs to ONLY rely on it's own stations and products (continental sovereignty)?

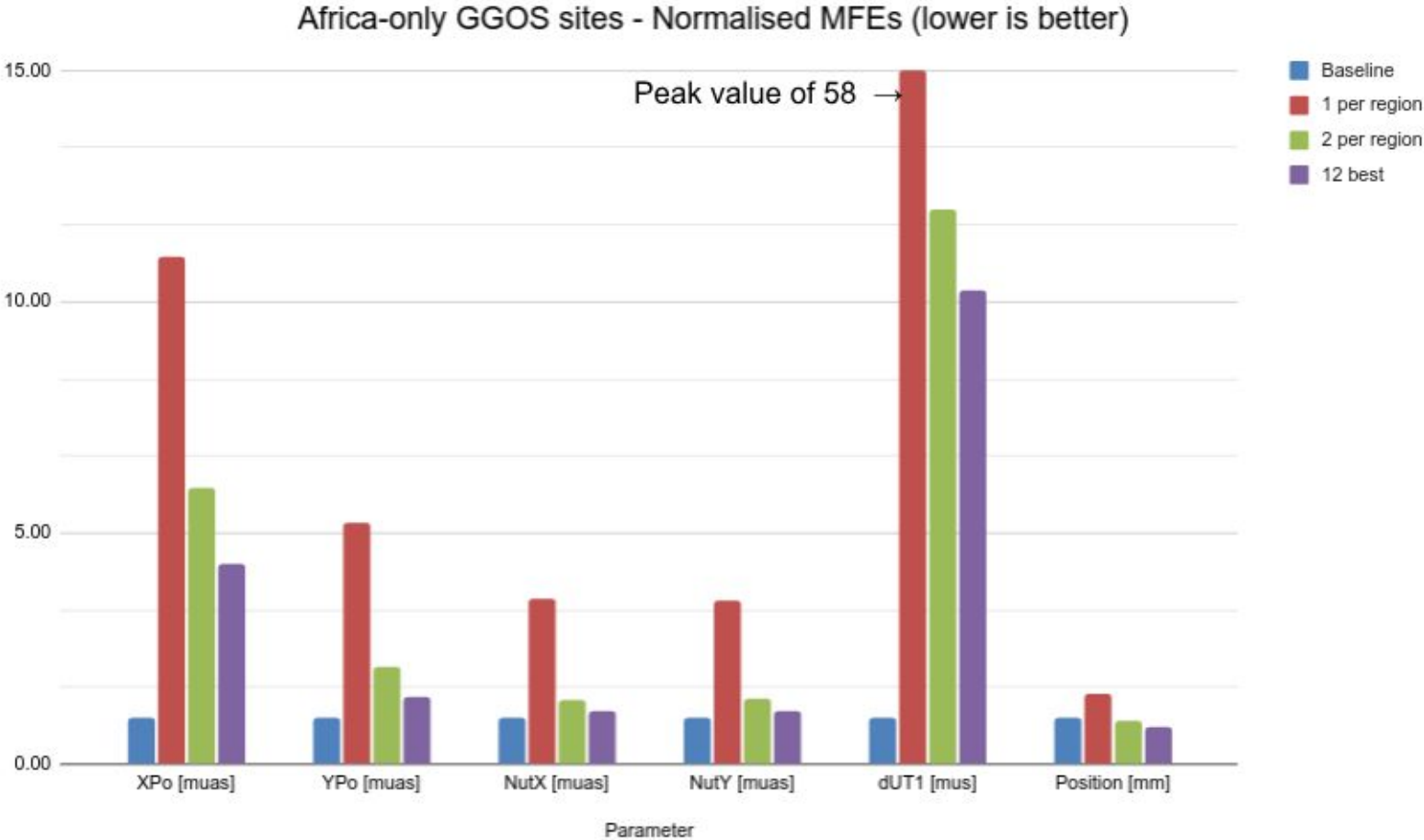
Comparative study by:

- considering EOPs and station coordinates
- in terms of MFEs and baseline repeatabilities

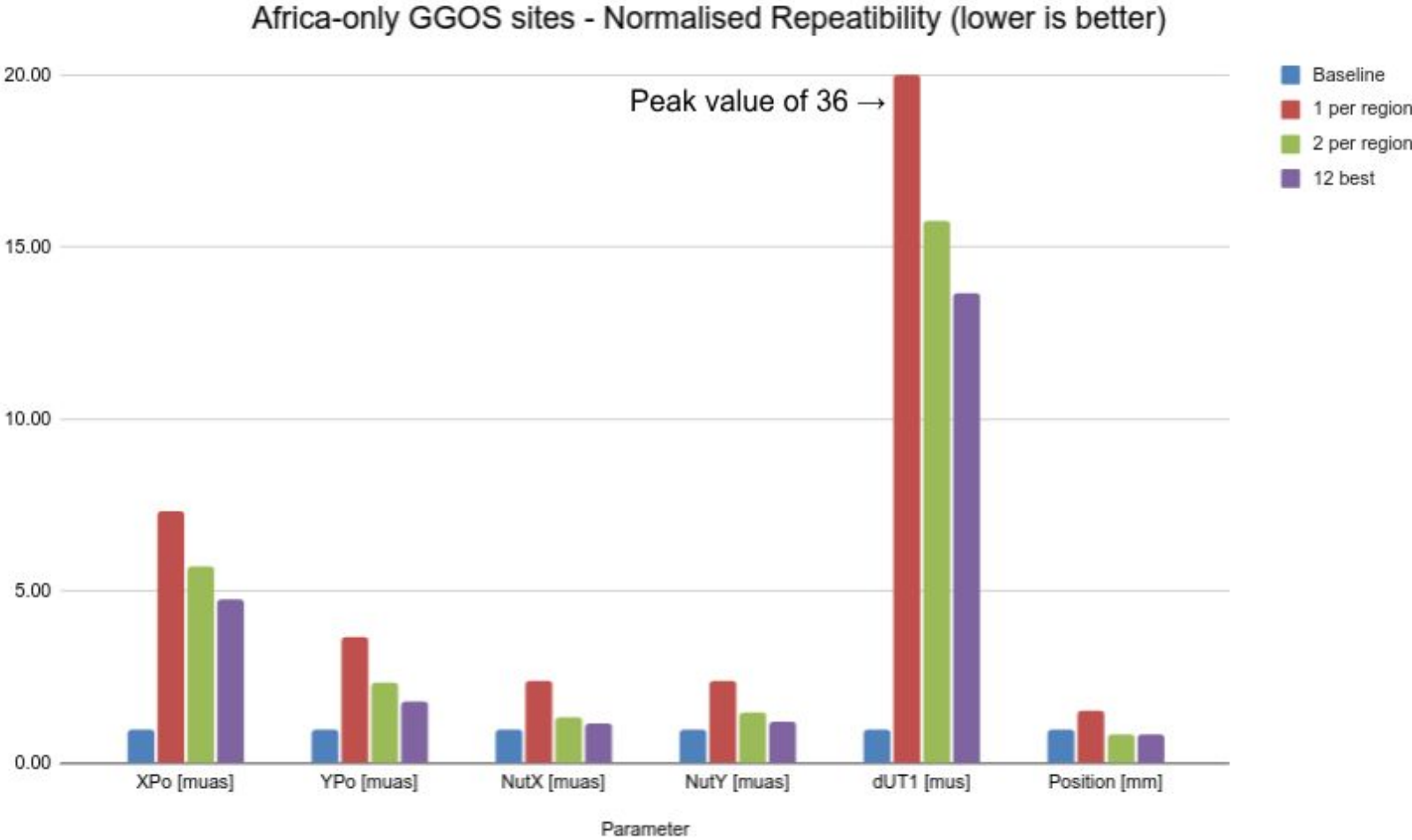
Approach:

- Current Non-African Reference: International VGOS network (as at current) without any African stations (HartRAO also not included)
- Clear the international VGOS network (assume no dishes on Earth)
- For African sites:
 - Choose regional data points with promising simulated results (from the initial simulations presented)
 - Simulate and compare with Current Non-African Reference:
 1. One VGOS per African Region - 5 in total
 2. Two VGOS per African Region - 10 in total
 3. Add 2 extra stations - East and South to account for continental geometry

3. Approach simulations from an Africa-only perspective



3. Approach simulations from an Africa-only perspective



3. Conclusions - Africa-only VGOS network

We estimate 10 stations at minimum are required

With < 10 stations we may still have an issue with UT1 - UTC

- can be addressed with longer E-W baselines
- we plan a simulation for this scenario

An African-only network of core sites should be able to enable an independent EOP product (we can have our own supply chain, except for the GNSS constellation)

- What about a SBAS system for Africa?
- Maybe even our own GNSS constellation in the far future?

SECTION 4:

Future Work

We still need to:

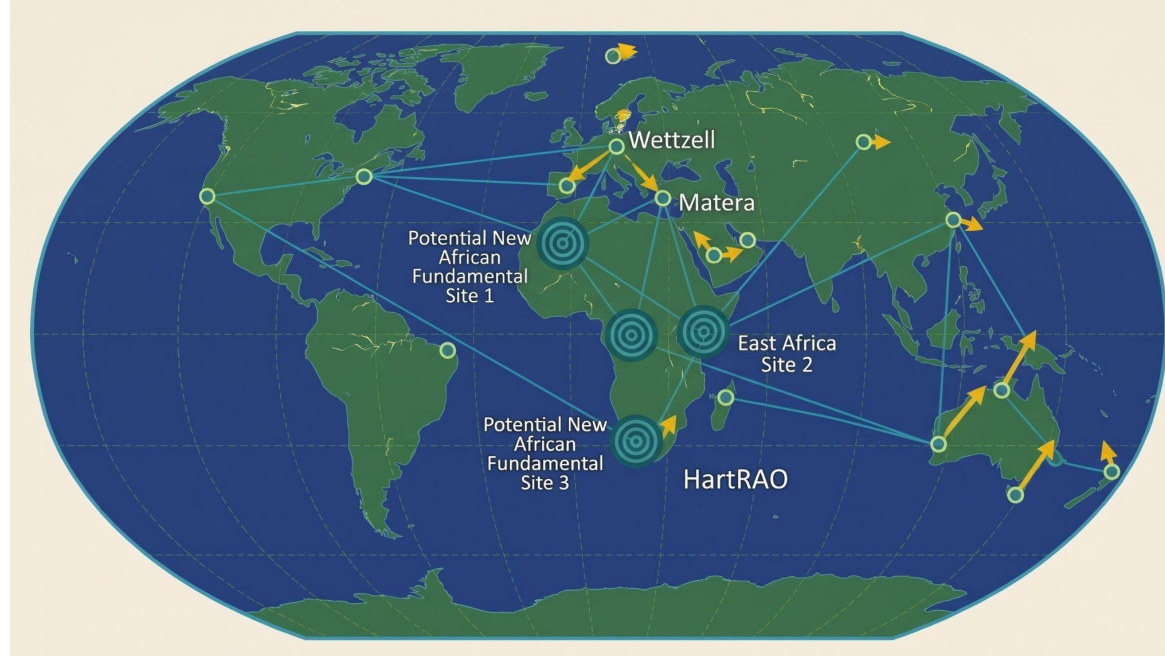
- Compile some data sets towards continental 'heat-maps'
- Data pack to provide (weighted) maps - request a collab for heat-map layering in ArcGIS
- Develop and avail Python scripts to automatically stack maps in ArcGIS
- Consider Multi-Criteria Decision Analysis (MCDA)

Where to from there (post project): *Per country collaborations*

- Find collaborators per-country to work on simulations and data layers per-country
- Focus on the remaining GGOS site requirements (next slide)

4. Consider GGOS - fundamental site requirements in a per-country study

1. Global Considerations	
	Celestial Frame - Sources in the South, source structure considerations, K-band frame
2. Land Considerations	
	Infrastructure refinements: Road Networks, HV power grids, Broadband fibre backbones
	Geological: Cratons and crystalline bedrock, Active fault lines (EARS), Seismicity and volcanism
3. Sky considerations:	
	Cloud fraction - NASA Giovanni portal / NASA Earth Observations (NEO)
	PWV - NASA Giovanni portal / European Centre for Medium-Range Weather Forecasts (ECMWF Copernicus Climate Data Store)
	Aerosol Optical Depth (AOD) - NASA Giovanni portal / CAMS (Copernicus Atmosphere Monitoring Service) repository



Summary

Initial simulation work concluded, models built, Africa-only network considered

Creating / polishing pipelines and scripts, to be released in the public domain

Per-country analysis packages to be done in collaboration with each country's representative(s) - who are interested?



Thank you

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SARAO
South African Radio
Astronomy Observatory



The SARAO Hartebeesthoek site
during April 2020.
Photo Credit: R Botha